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1. 1 sheet of Title Page and **66** sheets of Specification.
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Date: October 12, 2004

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[40124/04001]

U.S. PROVISIONAL PATENT APPLICATION

For

METHOD AND AN ARRAY FOR ADJUSTING A MAGNETIZATION OF A MAGNETIZABLE OBJECT, AND THE USE OF AT LEAST ONE ACTIVATIBLE DEGAUSSING ELEMENT TO DEGAUSS A PART OF A MAGNETIZED PORTION OF AN OBJECT

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A method and an array for adjusting a magnetization of a magnetizable object, and the use of at least one activatible degaussing element to degauss a part of a magnetized portion of an object

Background of the Invention

Field of the Invention

The present invention relates to a method and to an array for adjusting a magnetization of a magnetizable object, and to the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object .

Description of the Related Art

Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque or position of the shaft.

For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have a magnetically encoded region extending along a spatially accurately defined portion of the shaft. However, when a part of a shaft is magnetized in longitudinal direction, as described in WO 02/063262, it may happen that a region at the border between a non-magnetized portion and a magnetized portion of the shaft does not have well-defined magnetic properties. In

other words, a magnetization may be obtained in such a border area which has intermediate values between the magnetization of the non-magnetized and the magnetization of the magnetized portion. Such a non-well defined region deteriorates the sensitivity of a torque sensor or a position sensor, since it has an influence to the detection signal captured by a magnetic field detector.

Summary of the Invention

It is an object of the present invention to accurately define magnetized and unmagnetized portions of a magnetizable object.

This object is achieved by providing a method and an array for adjusting a magnetization of a magnetizable object, and by using at least one activatable degaussing element to degauss a part of a magnetized portion of an object according to independent aspects of the invention mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1, 21, and 32 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 20 relate to preferred embodiments of aspect 1. Aspects 22 to 31 relate to preferred embodiments of aspect 21.

1. aspect: A method for adjusting a magnetization of a magnetizable object, the method comprising the st eps of

providing an object having a magnetized portion extending along at least a part of the object;

arranging at least one degaussing element adjacent to the magnetized portion;

degaussing a part of the magnetized portion by activating the degaussing element to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object.

2. aspect: The method according to aspect 1, wherein an object is provided having the magnetized portion extending along the entire object.

3. aspect: The method according to aspect 1, wherein an object is provided having a plurality of alternating magnetized and unmagnetized portions.

4. aspect: The method according to any of aspects 1 to 3, wherein at least one the at least one degaussing element is a degaussing coil.

5. aspect: The method according to aspect 4, wherein the degaussing coil is arranged to surround a portion of the magnetized portion to be demagnetized.

6. aspect: The method according to any of aspects 1 to 5, wherein at least one the at least one degaussing element is an electromagnet.

7. aspect: The method according to any of aspects 4 to 6, wherein the at least one degaussing element is activated by applying a time-varying electric signal.

8. aspect: The method according to any of aspects 4 to 7,

wherein the at least one degaussing element is activated by applying an alternating current or an alternating voltage.

9. aspect: The method according to aspect 8, wherein the alternating current or the alternating voltage alternates with a frequency which is substantially smaller than 50 Hz.

10. aspect: The method according to aspect 8 or 9, wherein the alternating current or the alternating voltage alternates with a frequency less than 5 Hz.

11. aspect: The method according to any of aspects 1 to 10, wherein at least one the at least one degaussing element is a permanent magnet.

12. aspect: The method according to aspect 11, wherein the permanent magnet is activated by moving the permanent magnet in the vicinity of the object in a time-varying manner.

13. aspect: The method according to any of aspects 1 to 12, wherein the magnetized portion of the object is formed by magnetizing magnetizable material of the object by activating a magnetizing coil which is arranged to surround the portion of the object to be magnetized.

14. aspect: The method according to aspect 13, wherein the magnetizing coil is activated by applying a direct current or a direct voltage.

15. aspect: The method according to any of aspects 1 to 12, wherein the magnetized portion of the object is formed by

applying at least two current pulses to the object such that in a direction essentially perpendicular to a surface of the object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.

16. aspect: The method according to aspect 15, wherein, in a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

17. aspect: The method according to any of aspects 1 to 16, wherein a shaft is provided as the object.

18. aspect: The method according to aspect 17, wherein the shaft is one of the group consisting of an engine shaft, a reciprocable work cylinder, and a push-pull-rod.

19. aspect: The method according to any of aspects 1 to 18, wherein only one of the at least one degaussing element is activated at a time.

20. aspect: The method according to any of aspects 1 to 18, wherein at least two degaussing elements are activated at a time.

21. aspect: An array for adjusting a magnetization of a magnetizable object, comprising:

an object having a magnetized portion extending along at least a part of the object;

at least one degaussing element arranged adjacent to the magnetized portion, the at least one degaussing element being

adapted to be activated to degauss a part of the magnetized portion to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object.

22. aspect: The array according to aspect 21, wherein the object is a shaft.

23. aspect: The array according to aspect 22, wherein the shaft has a first unmagnetized portion and a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion.

24. aspect: The array according to aspect 23, having a first degaussing coil and having a second degaussing coil as degaussing elements, the first degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion.

25. aspect: The array according to aspect 24, wherein the first degaussing coil has a first connection and a second connection, and wherein the second degaussing coil has a first connection and a second connection, wherein a first voltage is applyable between the first connection and the second connection of the first degaussing coil, and a second voltage is applyable between the first connection and the second connection of the second degaussing coil.

26. aspect: The array according to aspect 24,

wherein the first degaussing coil has a first connection and a second connection, and wherein the second degaussing coil has a first connection and a second connection, wherein a voltage is applyable between the first connection of the first degaussing coil and the second connection of the second degaussing coil, wherein the second connection of the first degaussing coil is coupled with the first connection of the second degaussing coil.

27. aspect: The array according to any of aspects 24 to 26, having a first stopper coil and having a second stopper coil, the first stopper coil being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil, and the second stopper coil being arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil in such a manner that the first and second stopper coils are arranged between the first and second degaussing coils, wherein such an electrical signal can be applied to the first and the second stopper coils that a region between the first and second stopper coils is prevented from being demagnetized when at least one of the at least one degaussing element is magnetized.

28. aspect: The array according to any of aspects 21 to 27, wherein the magnetized portion is a longitudinally magnetized region of the object.

29. aspect: The array according to any of aspects 21 to 27, wherein the magnetized portion is a circumferentially magnetized region of the object.

30. aspect: The array according to any of aspects 21 to 29,

wherein the magnetized portion is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

31. aspect: The array according to aspect 30, wherein, in a cross-sectional view of the object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

32. aspect: Using at least one activatable degaussing element to degauss a part of a magnetized portion of an object to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object.

In the following, the above mentioned independent aspects of the invention will be described in more detail.

One idea of the invention may be seen in the fact that a magnetized object (e.g. magnetized with a treatment according to WO 02/063262) undergoes a post-treating in which an exactly definable border area between a magnetized region and a non-magnetized region of the magnetizable object is securely demagnetized to obtain a step-like spatial dependency in the magnetization which allows to separates a magnetized region from a non-magnetized region. For this purpose, a degaussing element like a coil is arranged adjacent to the magnetized portion to define the portion to be demagnetized and is degaussed by activating the degaussing element to form a well-defined demagnetized portion which is

arranged directly next to a remaining magnetized portion. Thus, the invention allows a fine-tuning of the magnetization profile along the length of the object. A gradual transition of the magnetization profile along an extension of the object is thus eliminated and replaced by a step-like magnetization profile. Thus, the magnetization properties are fine-tuned and may be adjusted to special requirements for a position sensor, or a torque sensor, increasing the sensitivity of the respective sensor.

The invention introduces the use of a degaussing element, preferably a magnetic coil, wherein the magnetic coil may be slid along the object (e.g. a magnetizable shaft, for instance made of a magnetizable steel). The magnetic coil is slid at such a position of the previously magnetized object that only such a part of the object which shall be demagnetized is located inside the coil opening. Then, an activating current is applied to the coil which has such an orientation, time dependence and strength that the elementary magnets of the portion to be demagnetized are at least partially randomized. Since a portion of the object arranged within the coil can be properly separated from a portion outside the coil, the spatial arrangement of a demagnetized portion and a of a remaining magnetized portion can be separated with high accuracy.

The concept of the invention to degauss a part of a partially magnetized object by surrounding a portion to be demagnetized with a magnetic coil as a degaussing element can be applied to a longitudinally magnetized shaft as disclosed by WO 02/063262, or can be alternatively applied to an object which has previously been magnetized according to the so-called PCME technology ("Pulse Current Modulated Encoding").

The PCME technology will be described in detail below and allows, by introducing a pulse current to the shaft, to generate, inside the object, an inner magnetized region which is surrounded by an outer magnetized region, wherein the magnetization direction of the two regions are oppositely to one another.

Such a magnetization configuration can be achieved by applying a pulse current directly to a predefined portion of a shaft as an example for the object. An effectively used encoding portion is defined by the positions on a shaft at which the current for forming a circumferential magnetic field are applied. The fine-tuning of such an encoding region is achieved with the method of the invention in which a border of the magnetized region in which the magnetization gradually decreases from a high value to zero is transformed into an almost step-like magnetization profile by applying a degaussing signal to a degaussing element.

In the following, preferred embodiments of the method for adjusting a magnetization of a magnetizable object according to the first independent aspect of the invention will be described. However, these embodiments also apply for the array for adjusting a magnetization of a magnetizable object and to the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object, according to other independent aspects of the invention.

According to the method of the invention, an object may be provided having the magnetized portion extending along the entire object. According to this embodiment, first, the entire object is magnetized, and then a remaining magnetized

portion is defined by demagnetizing selectable portions of the previously entirely magnetized object.

Alternatively, an object may be provided having a plurality of alternating magnetized and unmagnetized portions. According to this configuration, which is particularly advantageous for a position sensor of a reciprocating object wherein the position sensing is realized by measuring the magnetic field generated by the different magnetic regions of the reciprocating object, the object (like a reciprocating shaft) may first be magnetized in selectable portions, and afterwards the invention is implemented to fine-tune the magnetization of the sequence of magnetized and non-magnetized regions, by generating a magnetization profile which follows a mathematical step function.

At least one of the at least degaussing elements may be a degaussing coil. With a degaussing coil, i.e. a magnetic coil, the region of demagnetization can be properly defined by sliding the coil along the object, for instance a shaft.

Thus, the degaussing coil may be arranged to surround a portion of the magnetized portion to be demagnetized. This allows a proper positioning and definition of the region of the magnetized object to be demagnetized.

At least one of the at least one degaussing element may be an electromagnet. Using an electromagnet being controlled to form a time-dependent magnetic field is an alternative to a magnetic coil. Since an electromagnet can be provided in different shapes, sizes and geometries, it is also very suitable to properly define a portion to be demagnetized.

At least one of the degaussing elements may be activated by applying a time-varying electric signal. A time-varying electric signal (for instance an alternating current or an alternating voltage) produces a time-dependent magnetic field which, applied to a magnetized portion, may randomize the ordered magnetized elementary magnets, thus achieving a secure demagnetization.

Particularly, the at least one degaussing element may be activated by applying an alternating current or an alternating voltage.

The alternating current or the alternating voltage alternates preferably with a frequency which is substantially smaller than 50 Hz. Due to the so-called skin effect, it is preferred to use a sufficiently small frequency to allow a proper demagnetization also in the inner parts of the object, for instance close to the center of a shaft. This can be achieved by using sufficiently small frequencies, wherein, in a first approximation, the frequency value can be selected to be inversely proportional to the cross-sectional area of the object.

Thus, a proper value for the frequency of the time-varying demagnetization signal sensitively depends on the application used, but such a frequency is preferably considerably smaller than 50 Hz. For instance, a frequency region between 0.01 Hz and 20 Hz is suitable, a particularly preferred range is between 0.01 Hz and 5 Hz. When selecting parameters defining the degaussing signal, there is an interplay between time, amplitude and frequency of the applied electrical signal (e.g. voltage or current). As a rule of thumb, the demagnetization should be continued until an almost complete

randomization of the elementary magnets of the magnetized region to be demagnetized is achieved.

Further preferable, the alternating current or the alternating voltage may alternate with a frequency less than 5 Hz.

As an alternative to a configuration in which the degaussing element is realized as a coil or as an electromagnet, a permanent magnet may be used as degaussing element and may be activated by moving the permanent magnet in the vicinity of the object in a time-varying manner. By such a motion (e.g. a mechanical oscillation), a time-dependent demagnetization field is effective to the portion of the object to be demagnetized. Such a configuration makes the use of electrical degaussing signals indispensable, since a pure mechanical degaussing sequence is possible using a permanent magnet.

The magnetized portion of the object may be formed by magnetizing magnetizable material of the object by activating a magnetizing coil which is arranged to surround the portion of the object to be magnetized. Such a technology of magnetizing an object is disclosed, for instance, in WO 02/063262. According to this magnetization sequence, a portion of a magnetizable object (e.g. a metallic object like a shaft made of industrial steel) may be magnetized, wherein quality problems may occur at the border between the magnetized region and a non-magnetized region. Such a shaft may then be treated according to the fine-tuning of the magnetization profile according to the invention to improve the transition between magnetized and unmagnetized regions.

According to the described aspect, the magnetizing coil may be activated by applying a direct current or a direct voltage.

Alternatively to the magnetization method of WO 02/063262, the so-called PCME technology ("Pulse Current Modulated Encoding") technology may be applied, which will be described in detail below. According to this technology, the magnetized portion of the object may be formed by applying at least two current pulses to the object such that in a direction essentially perpendicular to a surface of the object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. According to this magnetization scheme, in a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

As the object, a shaft may be provided. Particularly, the shaft may be one of the group consisting of an engine shaft, a reciprocatable work cylinder, and a push-pull-rod.

Such an engine shaft may be used in a vehicle like a car to measure the torque of the engine. A reciprocatable work cylinder may be used in a concrete (cement) processing apparatus wherein one or more magnetically encoding regions on such a reciprocating work cylinder may be used to determine the actual position of the work cylinder within the concrete processing apparatus to allow an improved control of the operation of the reciprocating cylinder. A push-pull-rod, or a plurality of push-pull-rods, may be provided in a gear

box of a vehicle and may be provided with one or more magnetic encoded regions to allow a position detection of the push-pull-rod.

Preferably, only one of the at least one degaussing element is activated at a time. By activating each of the degaussing elements separately and one after another, the fine-tuning of the magnetization can be performed with a very high accuracy, and regions to remain magnetized are prevented from being demagnetized.

Alternatively, at least two degaussing elements may be activated at a time. This configuration allows a very fast fine-tuning and is therefore a very cost effective alternative.

In the following, preferred embodiments of the array for adjusting a magnetization of a magnetizable object according to the second independent aspect of the invention will be described. However, these embodiments also apply for the method for adjusting a magnetization of a magnetizable object and to the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object according to other independent aspects of the invention.

In the array, the object may be a shaft.

The shaft may have a first unmagnetized portion and may have a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion.

The array may have a first degaussing coil and may have a second degaussing coil as degaussing elements, wherein the first degaussing coil may be arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil may be arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion.

The first degaussing coil may have a first connection and may have a second connection. The second degaussing coil may have a first connection and may have a second connection. A first voltage may be applied between the first connection and the second connection of the first degaussing coil, and the second voltage may be applied between the first connection and the second connection of the second degaussing coil. In other words, according to this configuration, the two degaussing coils are electrically decoupled from one another. Thus, demagnetization signals for two borders between magnetized and unmagnetized portions may be generated one after another, yielding a high quality of the produced magnetization profile.

Alternatively, the first degaussing coil may have a first connection and may have a second connection, and the second degaussing coil may have a first connection and a second connection. A voltage may be applied between the first connection of the first degaussing coil and the second connection of the second degaussing coil, wherein the second connection of the first degaussing coil may be coupled with the first connection of the second degaussing coil. According to this configuration, a single voltage and thus a single voltage supply is sufficient to operate the array, since two connections of the degaussing coils are coupled allowing to

simultaneously produce a demagnetization signal for two borders between magnetized and unmagnetized portions.

Further, the array of the invention may have a first stopper coil and may have a second stopper coil, the first stopper coil being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil, and the second stopper coil may be arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil in such a manner that the first and second stopper coils are arranged between the first and second degaussing coils. Such an electrical signal can be applied to the first and the second stopper coils that the region between the first and second stopper coils are prevented from being demagnetized when the degaussing elements are activated. According to this configuration, small stopper coils or stopper inductors may be placed at a specific end of the degaussing elements, and the inductivity of the stopper coils may be significantly lower than the inductivity of the degaussing coils. Thus, the area which is affected by the demagnetization procedure can be defined even better.

The magnetized portion may be a longitudinally magnetized region of the object, for instance generated according to the technology described in WO 02/063262.

Alternatively, the magnetized portion may be a circumferentially magnetized region of the reciprocating object. This can be achieved by implementing the so-called PCME technology described below.

According to the latter aspect, the magnetized portion may be formed by a first magnetic flow region oriented in a first

direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction. Thus, in a cross-sectional view of the object, there may be the first circular magnetic flow having the first direction and a first radius, and the second circular magnetic flow may have the second direction and a second radius, wherein the first radius may be larger than the second radius.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig.1 to **Fig.7** show different views of a magnetizable shaft during a method for adjusting the magnetization of the shaft according to an embodiment of the invention.

Fig.8 shows an array for adjusting a magnetization of a shaft according to a first embodiment of the invention.

Fig.9 shows an array for adjusting a magnetization of a shaft according to a second embodiment of the invention.

Fig.10A, **Fig.10B** show an array for adjusting a magnetization of a shaft according to a third embodiment of the invention.

Fig.10C shows an array for adjusting a magnetization of a shaft according to a forth embodiment of the invention.

Fig.11A to **Fig.11C** show schemes for illustrating the invention.

Fig.12 to **Fig.67** illustrate the PCME technology which, according to the invention, is preferably used to magnetize a magnetizable object.

Detailed Description of Preferred Embodiments of the Invention

In the following, referring to Fig.1 to Fig.7, a method for adjusting a magnetization of a magnetizable object according to the invention will be described.

Fig.1 shows a cylindrical shaft 100 which is made of magnetizable industrial steel.

However, according to the scenario shown in Fig.1, the steel shaft 100 is demagnetized.

Fig.2 shows a configuration in which the magnetizable shaft 100 is partially magnetized, by the so-called PCME technology. For this purpose, a first metallic ring 200 is applied directly to the magnetizable shaft 100, and a second metallic ring 201 is attached to another part of the shaft

100. Then, a pulse electric current I_1 is applied to the rings 200, 201 to magnetize a portion 202 of the shaft 100. The magnetized portion 202 of the shaft 100 is formed by applying two current pulses to the shaft 100, each of the current pulses having a fast railing edge and a slow falling edge, such that in a direction essentially perpendicular to a surface of the shaft 100, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. In a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

Fig.2 also shows schematic current paths 203 which are strongly curved in a vicinity of the rings 200, 201. Thus, the magnetization is not very homogeneous in a portion directly neighbouring the rings 200, 201.

Fig.3 shows schematically a cross-section of the shaft 100, wherein, in a portion in which beforehand the (now removed) rings 200, 201 had been attached, a magnetized region 202 is generated. The shaft 100 has a first unmagnetized portion 301 and has a second unmagnetized portion 302, the magnetized portion 202 being arranged between the first unmagnetized portion 301 and the second unmagnetized portion 302. As can be seen in Fig.3, the magnetized portion 202 is formed by a first magnetic flow region 303 oriented in a first direction 305 and by a second magnetic region 304 oriented in a second direction 306, wherein the first direction 305 is opposite to the second direction 306. As can further be seen in Fig.3, in a cross-sectional view of the shaft 100, the first circular magnetic flow 303 has the first direction 305 and a first

radius, and the second circular magnetic flow 304 has the second direction 306 and a second radius, wherein the first radius is larger than the second radius.

However, when using the magnetized portion 202 as a magnetically encoded region for a torque sensor or a position sensor, only the central part of the magnetized region 202 can be used with for a high quality application, since only here the magnetization is homogeneous, whereas the magnetization is quite inhomogeneous at a border between one of the demagnetized regions 301, 302 and the magnetized region 202, i.e. a portion at which previously the rings 200, 201 had been attached.

As can be seen in **Fig.4**, the magnetization of the partially magnetized shaft 100 is adjusted by arranging a first degaussing coil 400 (coil axis parallel to shaft axis) adjacent the magnetic portion 202, i.e. at the border between the first unmagnetized portion 301 and the magnetized portion 202. Further, a second degaussing coil 401 (coil axis parallel to shaft axis) is arranged at a border between the magnetized region 202 and the second unmagnetized region 302.

As can be further seen in Fig.4, the part of the magnetized portion 202 being covered by the first degaussing coil 400 is degaussed and thus demagnetized by activating the first degaussing coil 400 to adjust the magnetization of the magnetizable shaft 100 by forming a demagnetized portion 500 of the shaft 100 directly adjacent to a remaining magnetized portion 501 of the shaft 100. Further referring to Fig.4, this is achieved by applying an alternating current I_2 to the first degaussing coil 400 with a frequency of 1 Hz. Thus, the elementary magnets within the demagnetized portion 500 are

almost randomized to eliminate any magnetization in this region. At the border between the demagnetized portion 500 and the remaining magnetized portion 501 of the shaft 100, the magnetization profile can be described by a step function, since the part of the shaft 100 to be demagnetized is clearly defined.

Referring to **Fig.5**, the demagnetization procedure is repeated with the portion to be demagnetized between the magnetized region 200 and the second unmagnetized region 302. For this purpose, an alternating current I_3 is applied to the second degaussing coil 401 to generate a second demagnetized portion 600, to define a remaining magnetized portion 601 which is spatially clearly defined.

After removing the degaussing coils 400, 401, the configuration of **Fig.7** is obtained showing a remaining magnetized region 601 in the center of the shaft 100, having two circumferential magnetized portions 303, 304 with oppositely oriented magnetizing directions.

In the following, referring to **Fig.8**, an array 800 for adjusting a magnetization of a shaft 100 according to a first embodiment of the invention will be described.

The array 800 for adjusting a magnetization of a magnetizable shaft 100 comprises the shaft 100 having a magnetized portion (not shown) extending along a part of the shaft 100. In the scenario of Fig.8, the magnetized portion extends along the part of the shaft 100 extending between a first degaussing coil 801 and a second degaussing coil 802. The part of the shaft 100 being magnetized has previously been magnetized according to the PCME technology. A part of the magnetized

portion is covered by the coils 801, 802 and will be demagnetized, as described in the following.

The first degaussing coil 801 is arranged adjacent to the magnetized portion, and the second degaussing coil 802 is arranged adjacent to the magnetized portion. Thus, the shaft 100 has a first unmagnetized portion and a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion. The first degaussing coil 801 is arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil 802 is arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion. The first degaussing coil 801 has a first connection 803 and a second connection 804, and the second degaussing coil 802 has a first connection 805 and has a second connection 806. A voltage can be applied between the first connection 803 of the first degaussing coil 801 and the second connection 806 of the second degaussing 802. The second connection 804 of the first degaussing 801 is coupled with the first connection 805 of the second degaussing coil 802.

In the following, the method of demagnetizing a portion of the magnetized portion of the shaft 100 will be described.

Applying a PCME electrical encoding pulse to the shaft 100 turned a large part of the shaft 100 into a sensing element. While this has the benefit that the sensor performance is a highest (at the center of the shaft 100), it has the disadvantage that the shaft 100 being largely magnetized is very "hot spotting" sensitive, i.e. sensitive to a nearby ferromagnetic material.

This means that a large part of the shaft 100, almost from end to end, is sensitive to applied mechanical forces. Equally, the resulting magnetic field changes at the shaft 100 surface, stretch over the entire shaft 100 length. Such a dimensionally large magnetic field can be easily attracted or influenced in shaped by other ferromagnetic devices that are placed (or moved) near the magnetically encoded shaft 100.

Therefore, the magnetic encoded region should in axial direction kept reasonably short. Even better it will be to place pinning fields in either side of the magnetically encoded region. In the example shown in Fig.8, a large part of the shaft 100 has been magnetically encoded, and subsequently, the magnetic encoding will be deleted on either side of the desired location of the remaining magnetized portion of the torque sensor shaft 100.

According to embodiment shown in Fig.8, this is achieved by sliding the shaft ends into a radially tightly wound coil (inductor) 801, and 802, respectively. By applying an alternating electrical current through the inductors 801, 802, the magnetic sensor encoding will be reduced in strength, or even entirely erased. As can be seen, the field cancellation efficiency is almost 100% in the region of the shaft 100 which is surrounded by the degaussing coils 801, 802, and is smaller in the center of the shaft 100.

However, as seen in Fig.8, applying the alternating current to both coils 801, 802 at the same time will to a larger degree have an effect also on the sensor region that lies between the two erasing coils 801, 802. With other words, this approach will not only delete the magnetic encoding at

the shaft ends, but also partially in the middle section of the shaft 100.

Thus, when driving the magnetic field cancellation inductors 801, 802 simultaneously, the magnetic field cancellation efficiency is stretching beyond the location where the magnetic field cancellation inductors 801, 802 end. Consequently, the section between the degaussing coils 801, 802 will also be affected. This means that the magnetic encoding that may have been present in the section between the degaussing coils 801, 802 will be, to some extent, erased as well.

In the following, referring to **Fig.9**, an array 900 for adjusting a magnetization of the shaft 100 according to a second embodiment of the invention will be described, which is further improved compared to the embodiment shown in Fig.8.

According to Fig.9, only one of the coils 801, 802 at one time is connected to the alternating electrical current. In other words, according to Fig.9, a first voltage may be applied between the first connection 803 and the second connection 804 of the first degaussing coil 801, and independently from this, a second voltage may be applied between the first connection 805 and the second connection 806 of the second degaussing coil 802, one voltage being applied after the other.

As can be seen from the graph in Fig.9, the field cancellation efficiency is significantly reduced in the area between the coils 801, 802 compared to the array 800, so that the portion related to the remaining magnetization in the

center of shaft 100 is prevented from being demagnetized in an improved manner.

According to Fig.9; even better results are achieved when operating the magnetic field cancellation inductors 801, 802 one after each other. The magnetic field cancellation efficiency is dropping noticeably in the spacing between the two degaussing coils 801, 802. However, the magnetic encoding that may have been present in the section between the two degaussing coils 801, 802 may still be erased to a smaller extent in a non-uniform way.

In the following, referring to **Fig.10A**, an array 1000 for adjusting a magnetization of the shaft 100 according to a third embodiment of the invention will be described.

According to the embodiment shown in Fig.10, the array has a first stopper coil 1001 and has a second stopper coil 1002, the first stopper coil 1001 being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil 801, and the second stopper coil 1002 is arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil 802 in such a manner that the first and second stopper coils 1001, 1002 are arranged between (intermediate, i.e. sandwiched between) the first and second degaussing coils 801, 802, wherein such a voltage can be applied to the first and second stopper coils 1001, 1002 that the region between the first and second stopper coils 1001, 1002 is prevented from being demagnetized when the degaussing elements 801, 802 are magnetized.

As can be seen in Fig.10, when using stopper inductors 1001, 1002 (these are inductors that are placed at a specific end

of the magnetic field cancellation inductors 801, 802, and the inductivity of the stopper inductors 1001, 1002 is significantly lower than the inductivity of the magnetic field inductors 801, 802), the area which is affected by the magnetic field cancellation inductors 801, 802 can be much clearer defined. An additional benefit is such that a magnetic field cancellation system design can be operated in one step (no sequential operation of applying voltages is necessary).

As one can see from Fig.10A, **Fig.10B**, a single current signal is applied to the coils 801, 802, 1001, 1002, and the current flows between the first connection 803 of the first degaussing coil 801 and the second connection 806 of the second degaussing coil 802. After having flown through the first degaussing coil 801 and before flowing through the second degaussing coil 802, the current flows through the first stopper coil 1001 and the second stopper coil 1002. However, the flowing direction of the current in the degaussing coils 801, 802 is the same, and the flowing direction of the current in the stopper coils 1001, 1002 is the same. The flowing direction of the current in any of the degaussing coils 801, 802 is opposite to the flowing direction of the current in any of the stopper coils 1001, 1002. The number of windings of each of the degaussing coils 801, 802 is larger than the number of windings of each of the stopper coils 1001, 1002. Thus, the strength of the magnetic field generated by any of the coils 801, 802, 1001, 1002 is adjusted by selecting the number of windings, and by adjusting the amplitude of the applied current, to achieve proper magnetic field values generated by any of the coils 801, 802, 1001, 1002.

In the following, referring to **Fig.10C**, an array 1050 for adjusting a magnetization of the shaft 100 according to a forth embodiment of the invention will be described.

According to the embodiment shown in Fig.10C, each of the coils 801, 802, 1001, 1002 has two connections with separate current sources I_1, I_2, I_3, I_4. Thus, the current to flow through any of the coils 801, 802, 1001, 1002 can be adjusted separately for any of the coils 801, 802, 1001, 1002. The strength of each of these currents may be adjusted individually to allow to set the magnetization profile along the shaft 100 in desired manner. According to the embodiment of Fig.10C, the current values are selected as follows: $I_1=I_4$, $I_2=I_3$, $|I_2|<|I_1|$. According to Fig. 10C, the number of windings (4) is identical for each of the coils 801, 802, 1001, 1002.

In the following, referring to Fig.11A to Fig.11C, a background and explanation for the invention is given.

Fig.11A shows a magnetized shaft 100 and a magnetic field profile 1100 around the shaft 100. When the PCME encoding signal has been applied to the entire shaft, then the magnetized shaft 100 is stretching from end to end.

As can be seen in **Fig.11B**, when a ferromagnetic object 1101 is located in a surrounding area of the magnetized shaft 100, "hot spotting" may occur, i.e. a strong sensitivity to nearby ferromagnetic material 1101. In such a case a magnetic encoded sensor may be (but does not have to be) very sensitive when a ferromagnetic object 1101 will touch one of the shaft 100 ends or is changing its position near the shaft 100. (Example: rotating gear tooth wheel). As can be seen in

Fig.11C, a domino effect can occur. Such effects may be reduced or eliminated by the invention.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to magnetize a magnetizable object which is then partially demagnetized according to the invention. In the following, the PCME technology will partly described in the context of torque sensing. However, this concept may implemented in the context of position sensing as well.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	**Description**	**Category**
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting		Sensitivity to
nearby Ferro magnetic material		Specification

IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing Electronics	
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are

at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very

simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the shaft and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14**, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the

magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.

- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)

- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).

- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used

DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to **Fig.21**, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location /

position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to

close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a

combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to **Fig.25**, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to **Fig.26**, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have

been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30**, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to **Fig.31**, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to **Fig.32**, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to **Fig.33**, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to **Fig.34**, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to **Fig.35**, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will

penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using

electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF)

encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to **Fig.43**, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three

locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to **Fig.45**, magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46**, when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47**, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.

Referring to **Fig.48**, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic

material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but

requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to **Fig.54**, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already

existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to

the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a

wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment - & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit

(SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.

☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.

As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present

invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, …) and so does the processing equipment required. Some of the available magnetostriction sensing technologies do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)

- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

An array for adjusting a magnetization of a magnetizable object, comprising:

an object having a magnetized portion extending along at least a part of the object;

at least one degaussing element arranged adjacent to the magnetized portion, the at least one degaussing element being adapted to be activated to degauss a part of the magnetized portion to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object;

wherein the object is a shaft;

wherein the shaft has a first unmagnetized portion and a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion;

having a first degaussing coil and having a second degaussing coil as degaussing elements, the first degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion;

wherein the first degaussing coil has a first connection and a second connection, and wherein the second degaussing coil has a first connection and a second connection, wherein a first voltage is applyable between the first connection and the second connection of the first degaussing coil, and a second voltage is applyable between the first connection and the second connection of the second degaussing coil;

having a first stopper coil and having a second stopper

coil, the first stopper coil being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil, and the second stopper coil being arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil in such a manner that the first and second stopper coils are arranged between the first and second degaussing coils, wherein such an electrical signal can be applied to the first and second the stopper coils that a region between the first and second stopper coils is prevented from being demagnetized when the degaussing elements are magnetized;

wherein the magnetized portion is a circumferentially magnetized region of the reciprocating object.

Abstract

A method and an array for adjusting a magnetization of a magnetizable object, and the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object

A method for adjusting a magnetization of a magnetizable object, the method comprising the steps of providing an object having a magnetized portion extending along at least a part of the object, arranging at least one degaussing element adjacent to the magnetized portion, and degaussing a part of the magnetized portion by activating the degaussing element to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object. (Fig.10)

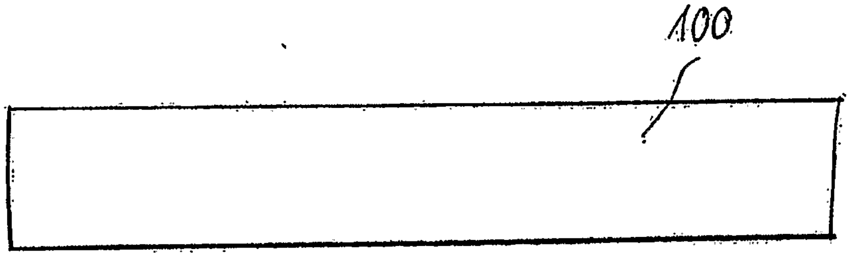


Fig. 1

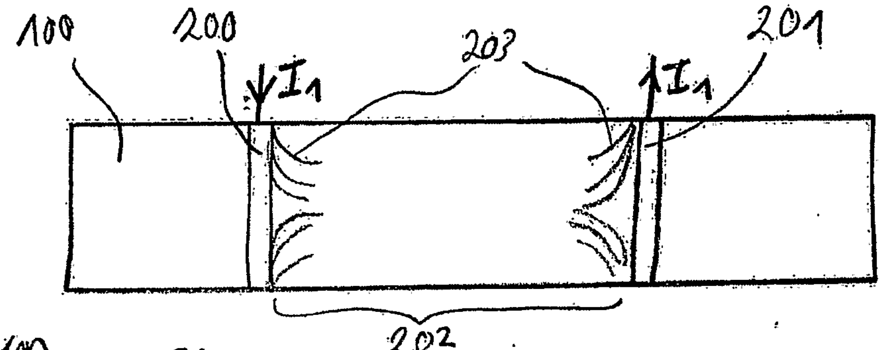


Fig. 2

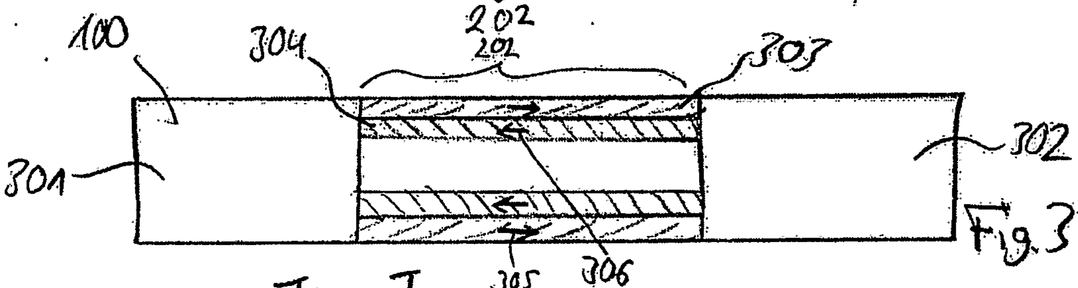


Fig. 3

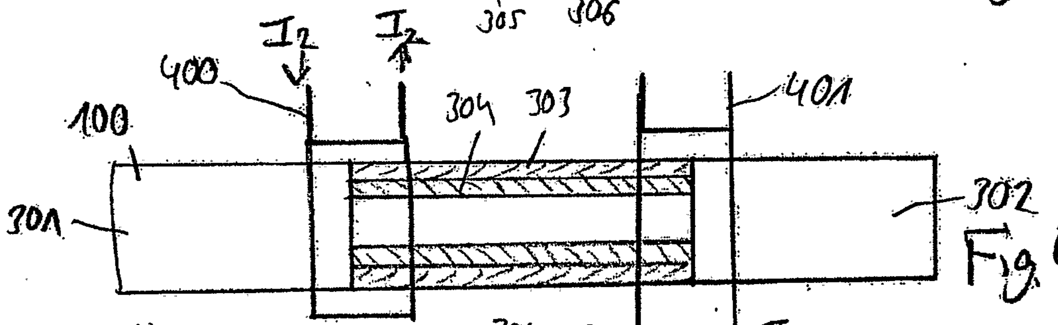


Fig. 4

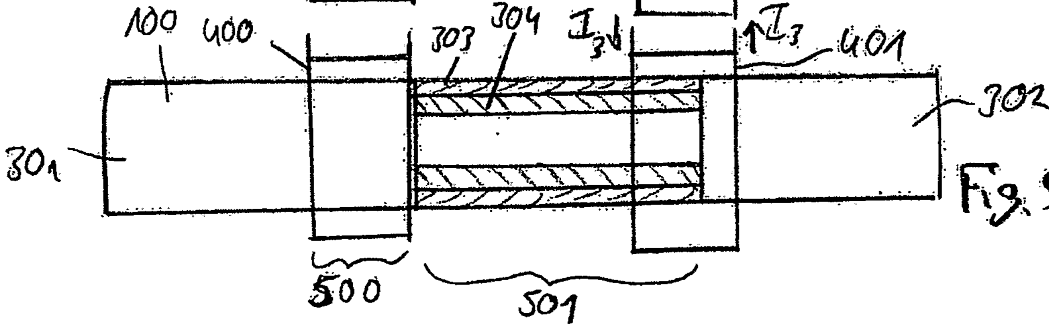


Fig. 5

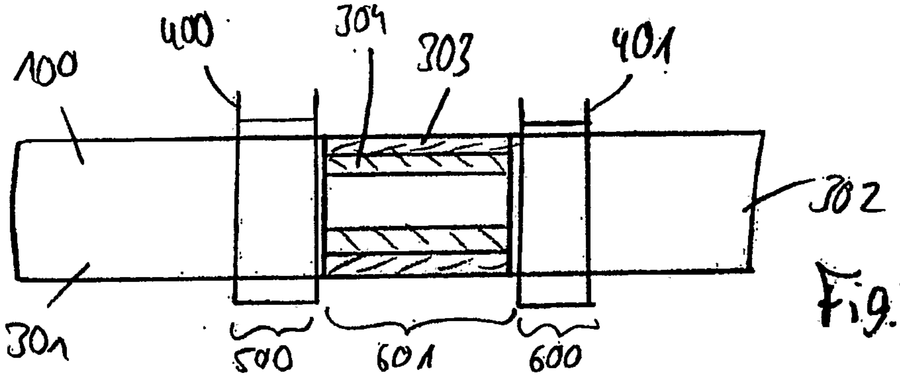


Fig. 6

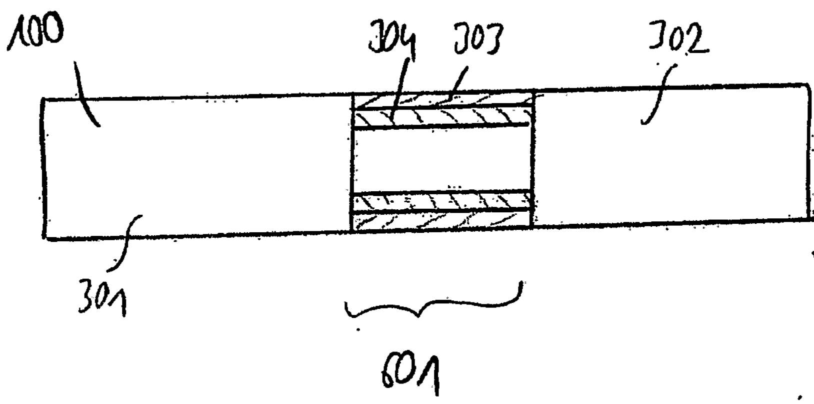


Fig. 7

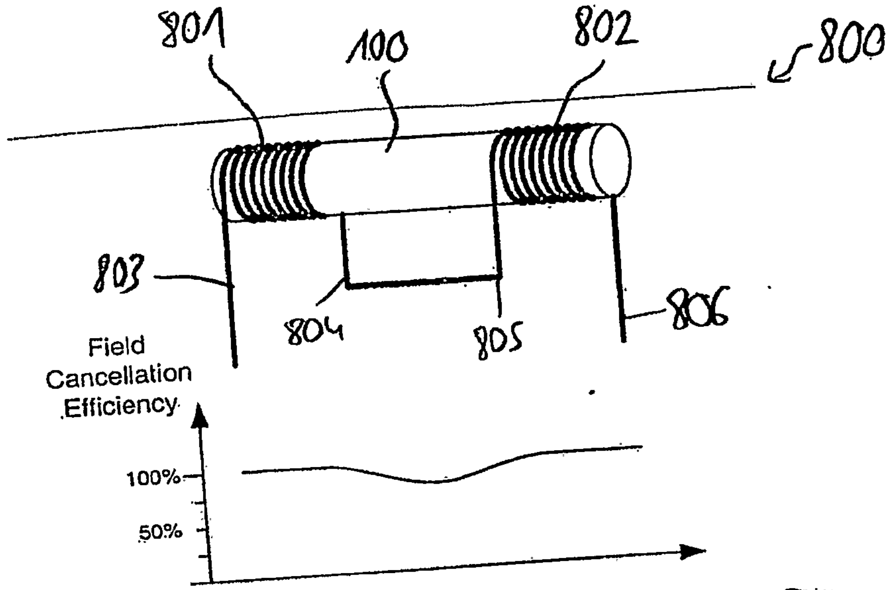
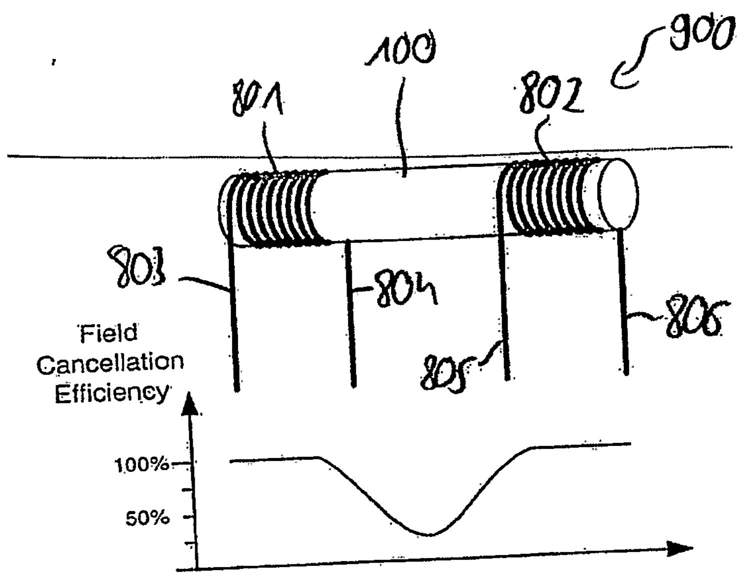

801
100
802
800
803
804
805
806
Field
Cancellation
Efficiency
100%
50%

Fig. 8


900
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801
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803
804
805
806
Field
Cancellation
Efficiency
100%
50%

Fig. 9

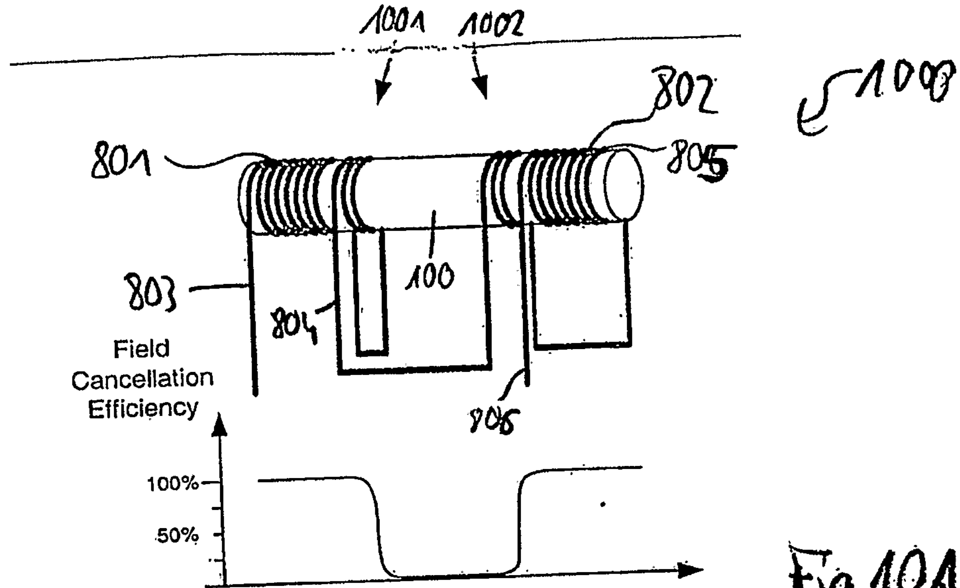


Fig. 10A

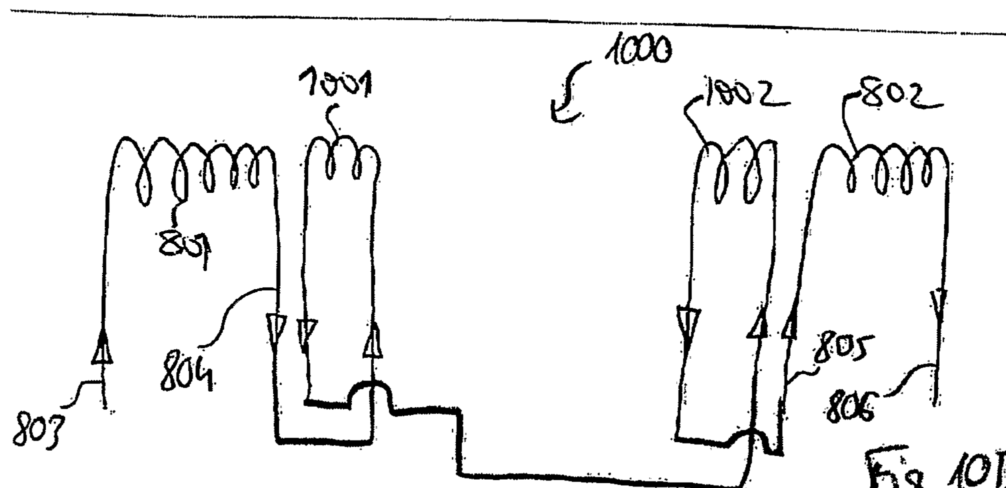


Fig. 10B

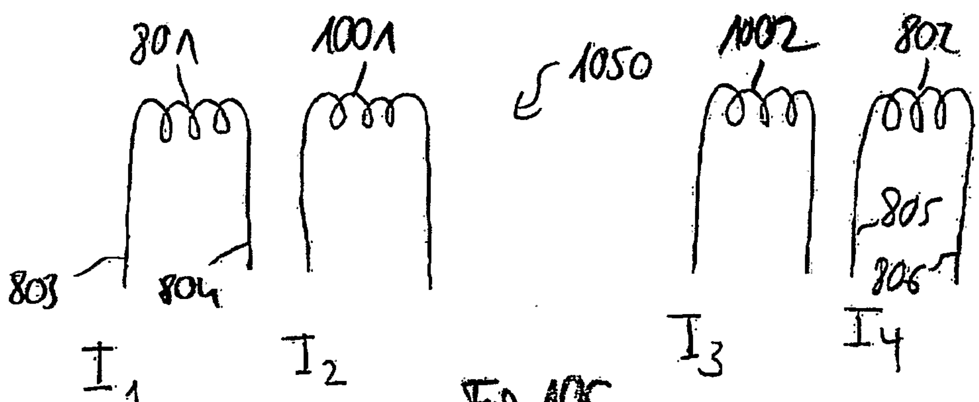


Fig. 10C

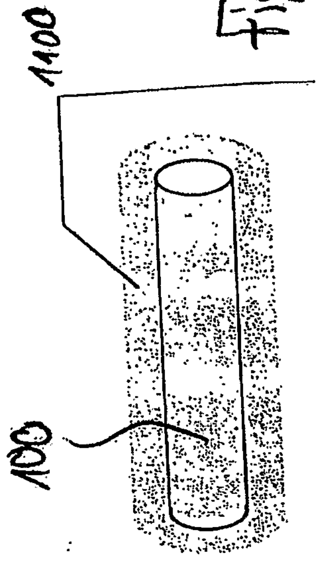


Fig. 11A

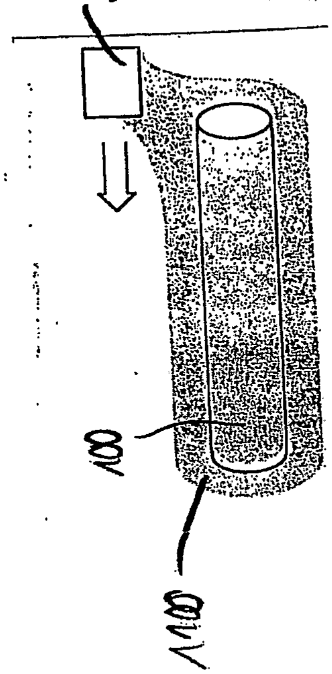


Fig. 11B

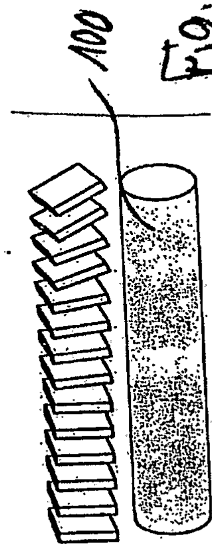


Fig. 11C

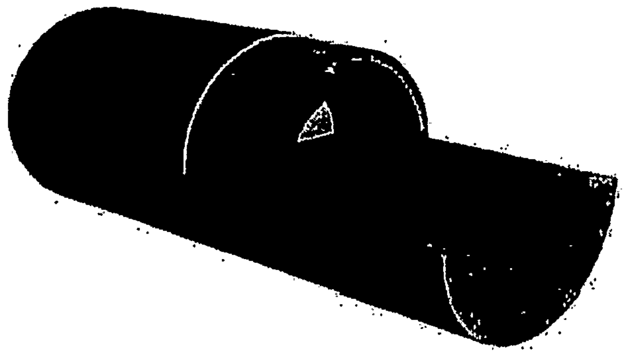


Fig. 12

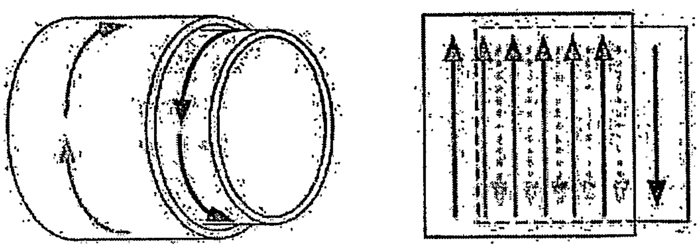


Fig. 13

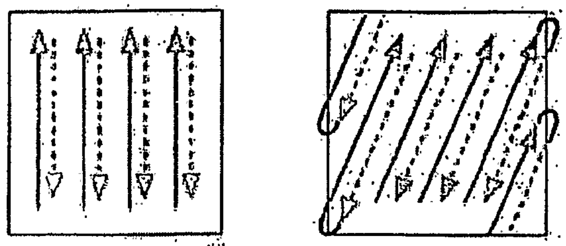


Fig. 14

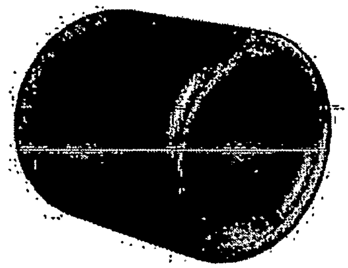


Fig. 15

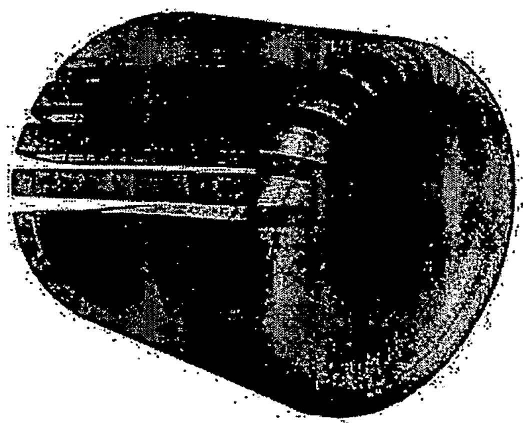


Fig. 16

Fig. 17

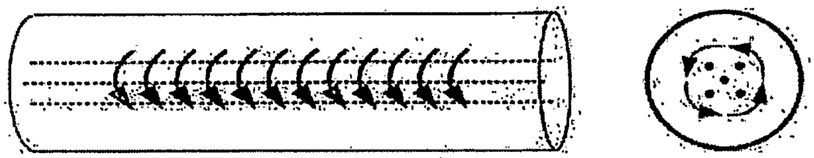


Fig. 18

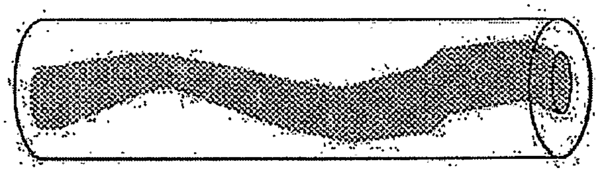


Fig. 19

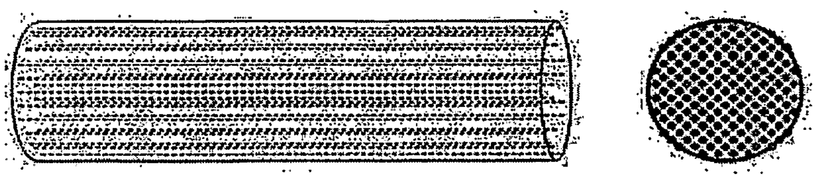


Fig. 20

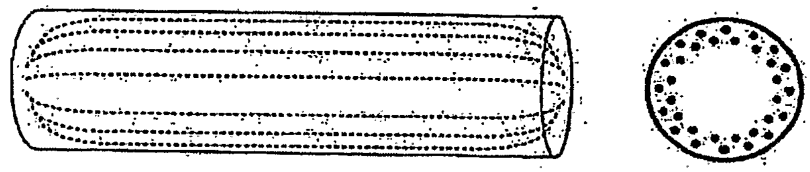


Fig. 21

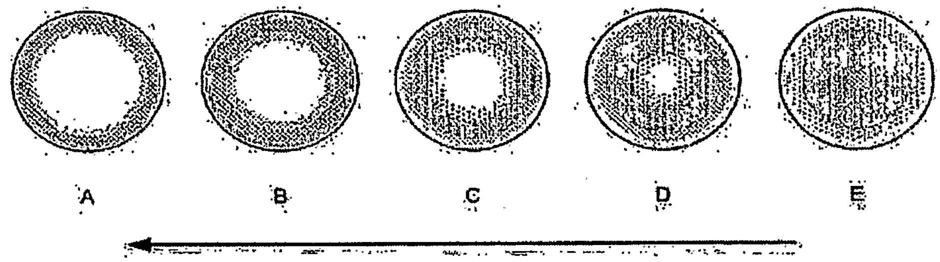


Fig. 22

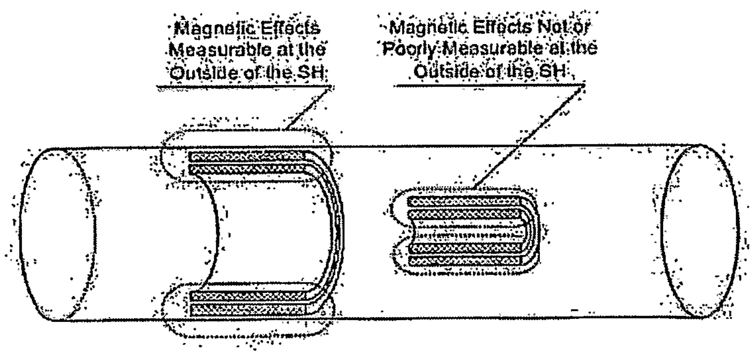
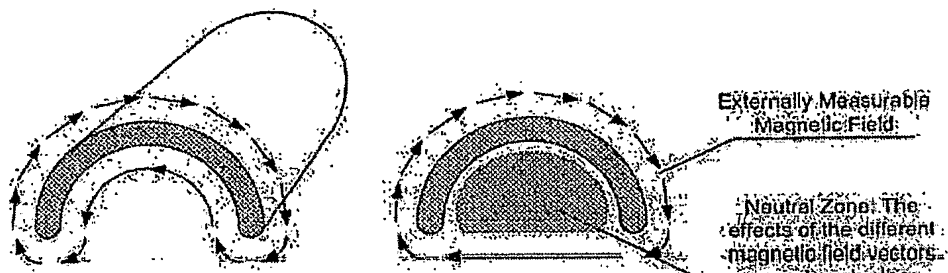


Fig. 23

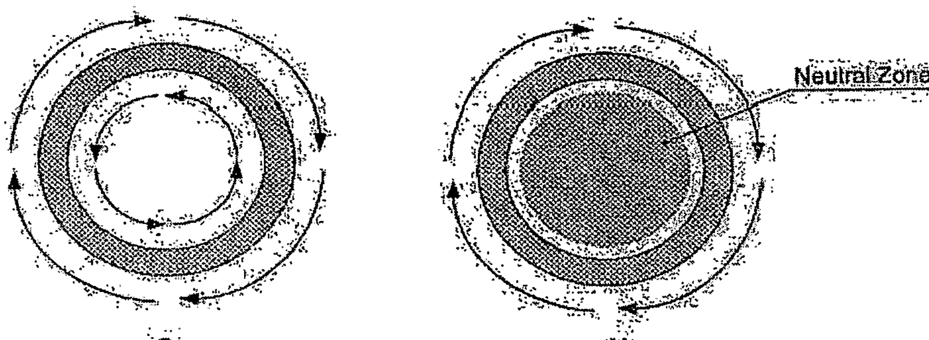
A B C D

Fig. 24



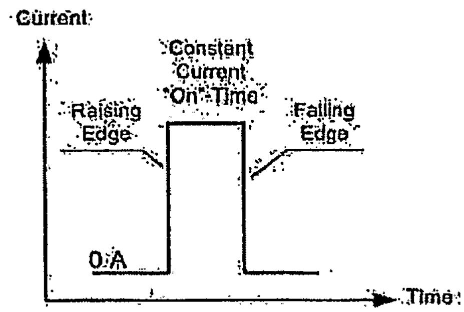
E F

Fig. 25



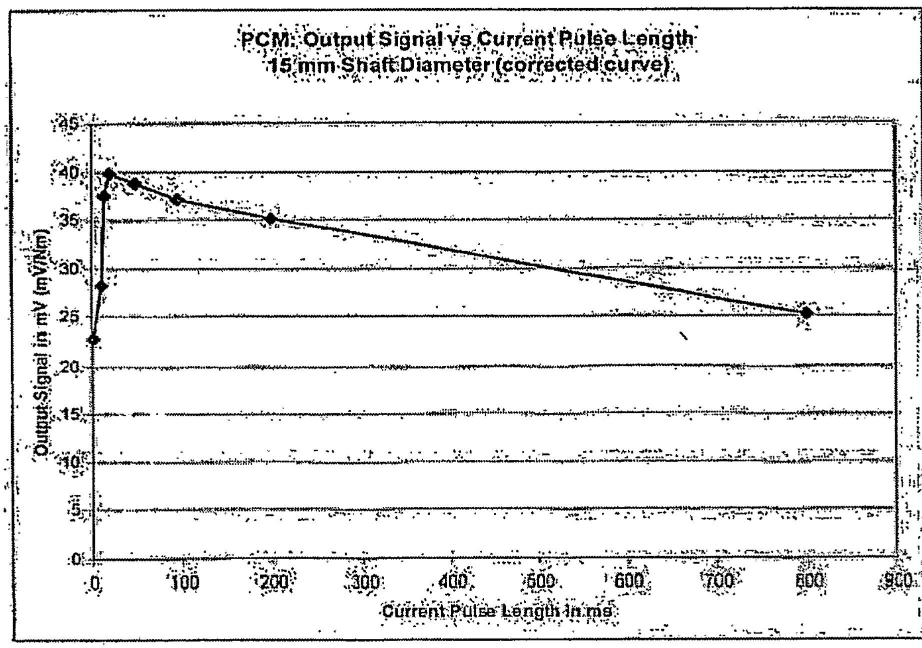
G H

Fig. 26



Current
Constant
Current
On Time
Raising
Edge
Falling
Edge
0 A
Time

Fig. 27



PCM: Output Signal vs Current Pulse Length
15 mm Shaft Diameter (corrected curve)
Output Signal in mV (mV/Nm)
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
Current Pulse Length in ms

Fig. 28

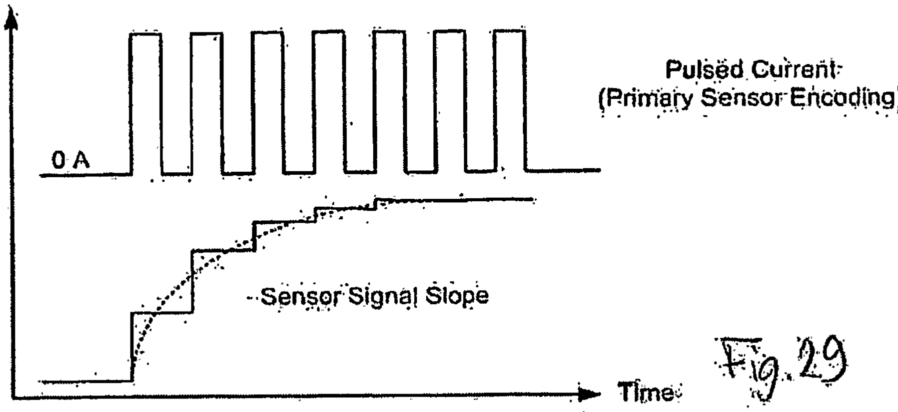


Fig. 29

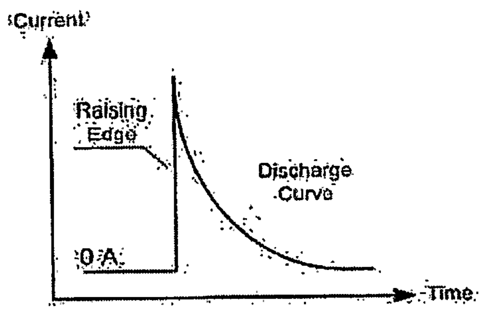


Fig 30

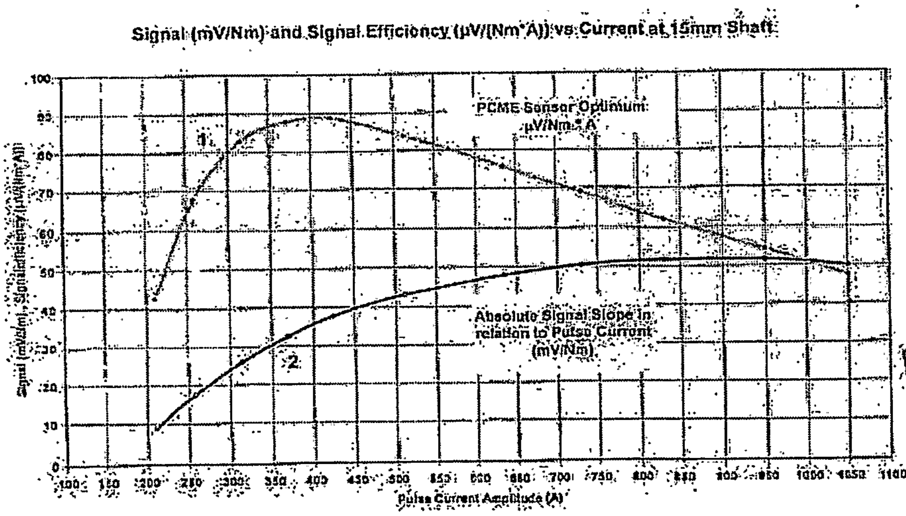


Fig 31

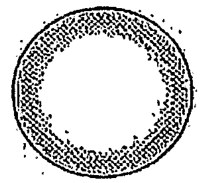


Fig. 32

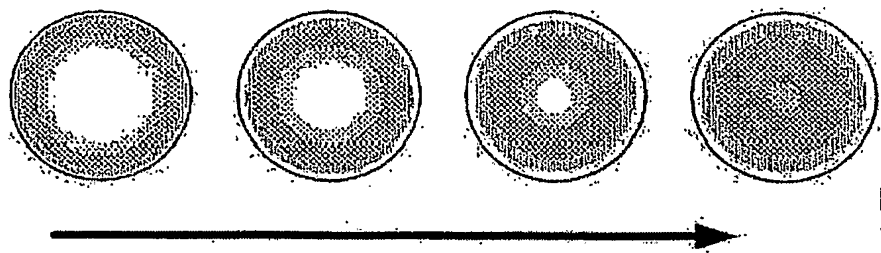


Fig. 33

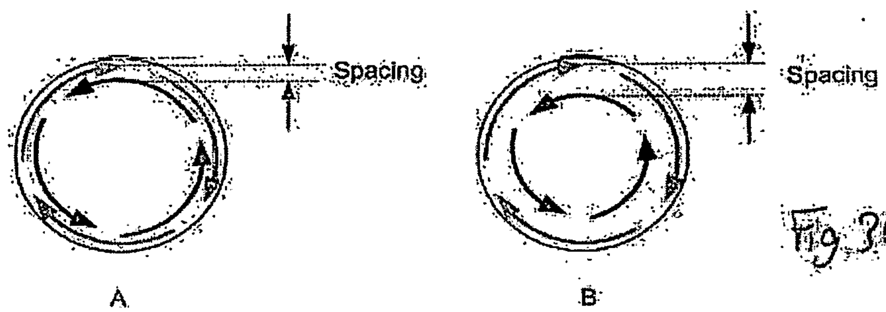


Fig. 34

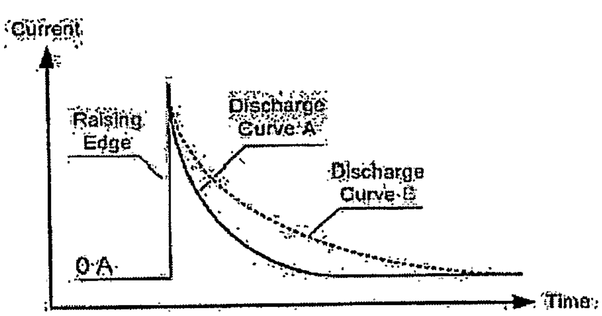


Fig. 35

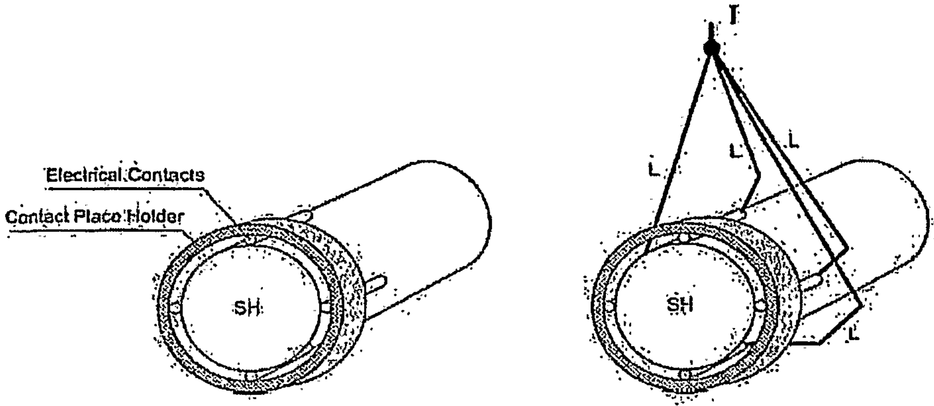


Fig 36

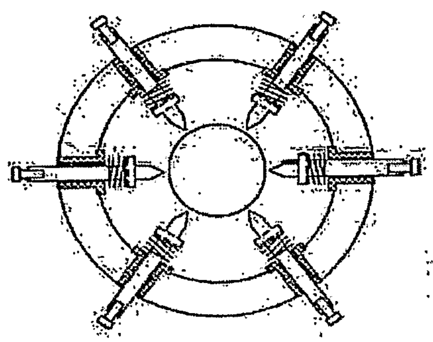


Fig 37

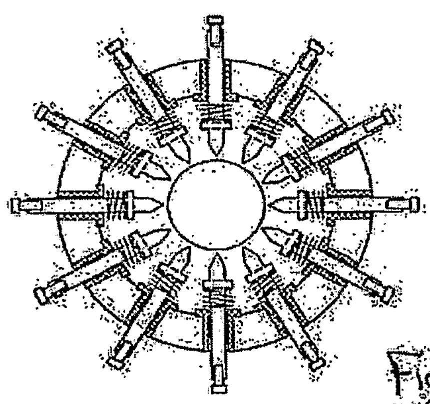


Fig 38

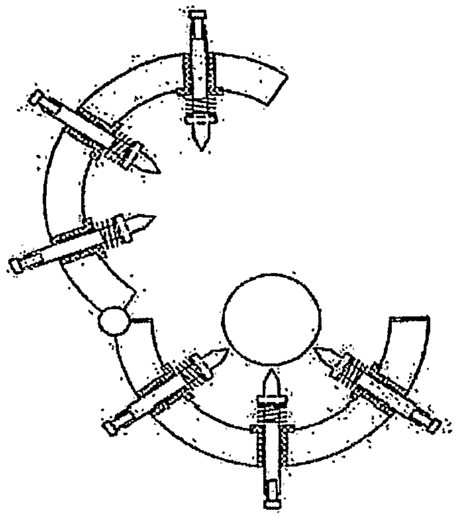


Fig 39

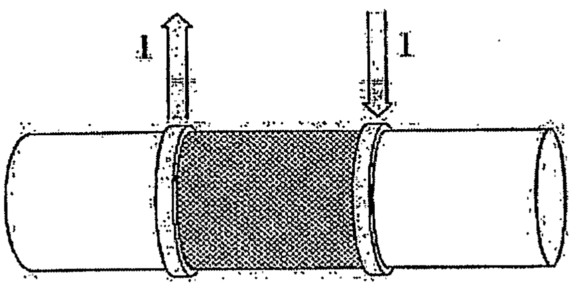


Fig 40

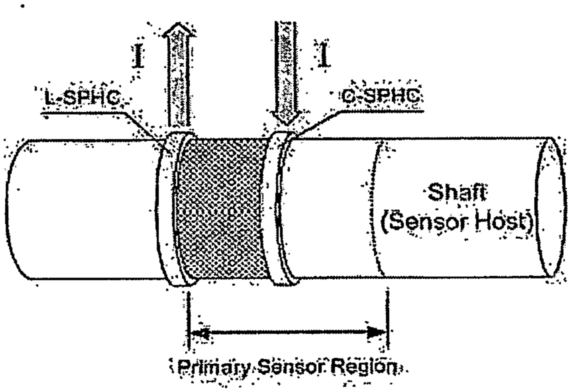


Fig 41

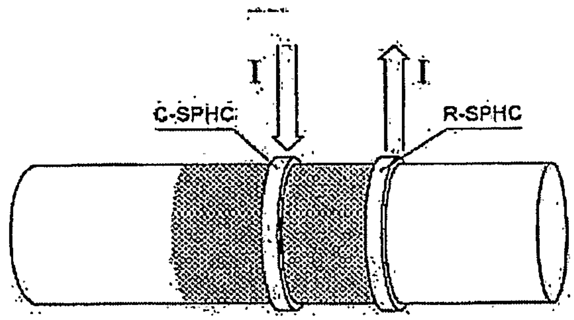


Fig 42

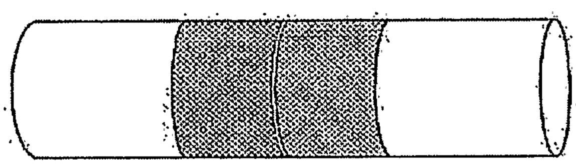


Fig 43

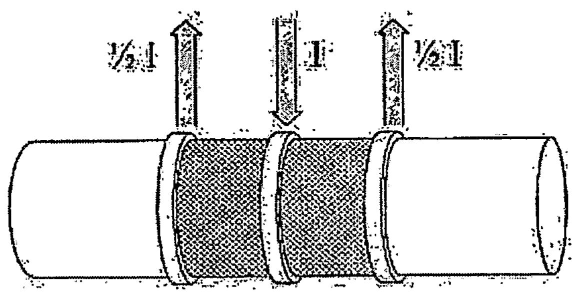


Fig 44

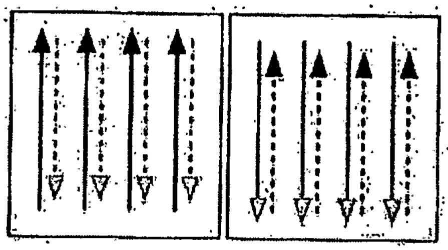


Fig. 45

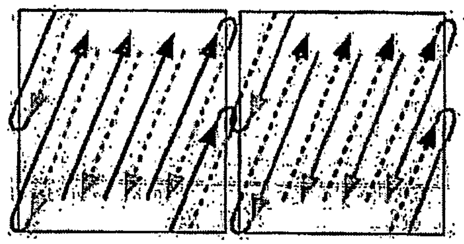


Fig. 46

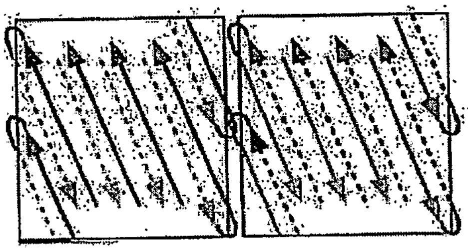
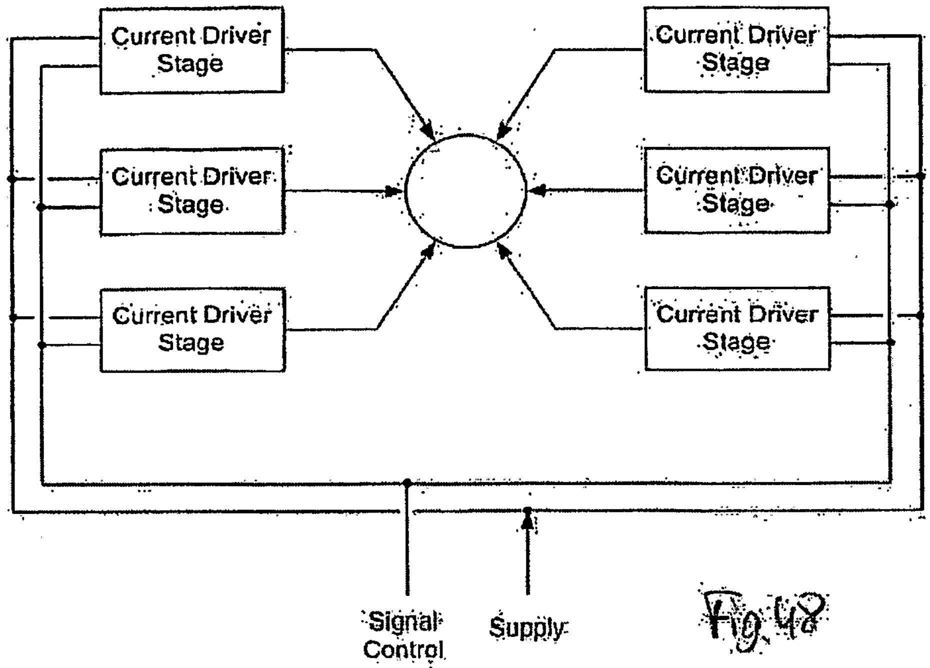
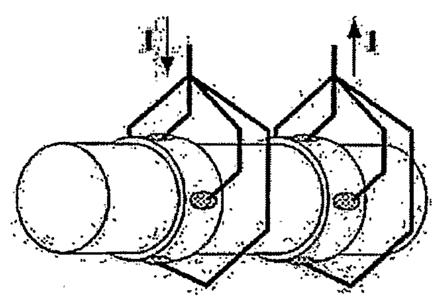


Fig. 47



Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply

Fig. 48



I
I

Fig. 49

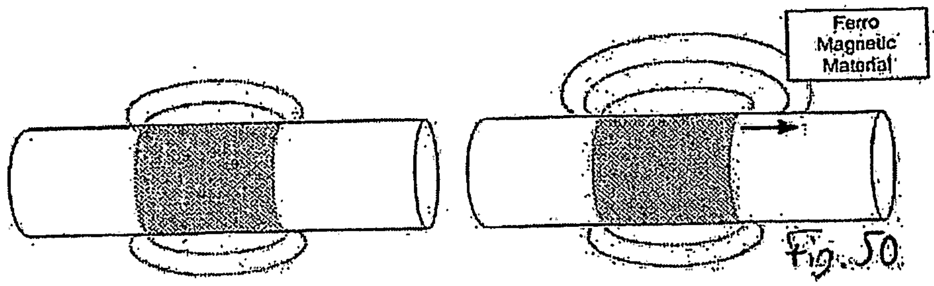


Fig. 50

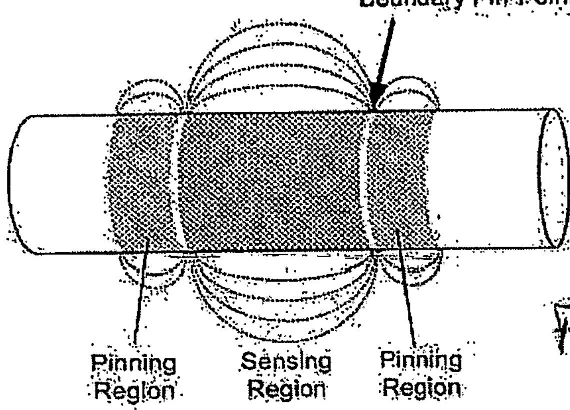


Fig. 51

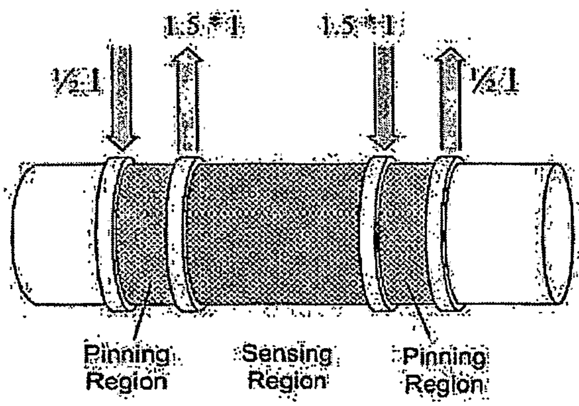


Fig. 52

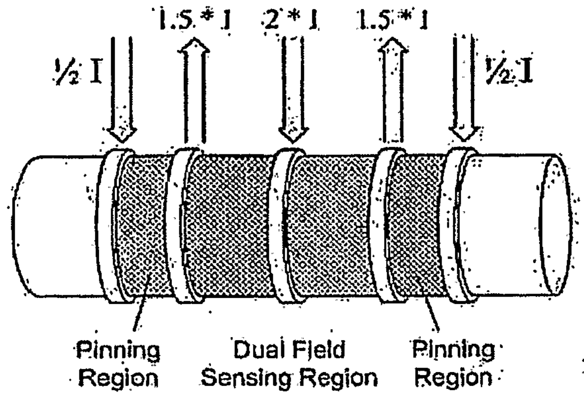


Fig. 53

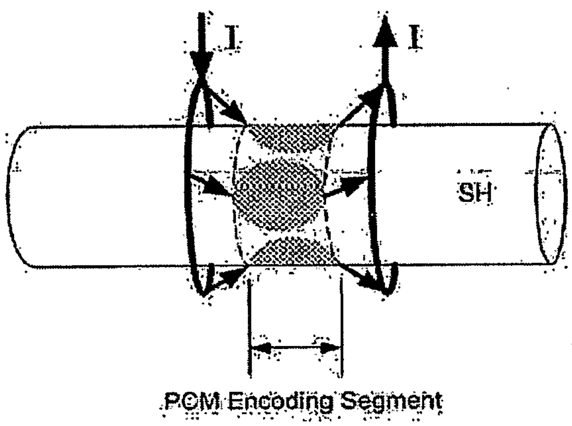


Fig. 54

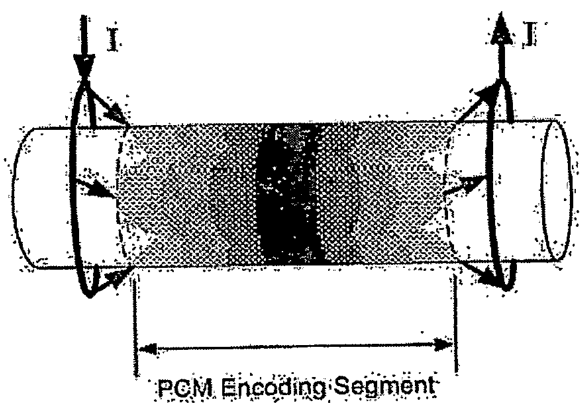


Fig. 55

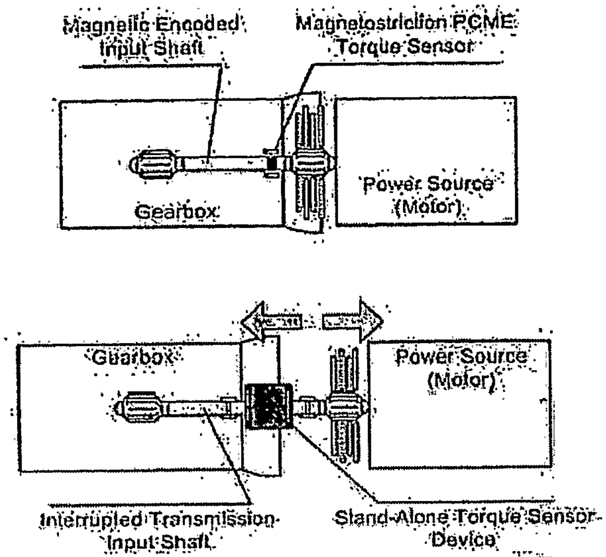

Magnetic Encoded Input Shaft
Magnetostriction PCME Torque Sensor
Power Source (Motor)
Gearbox
Gearbox
Power Source (Motor)
Interrupted Transmission Input Shaft
Stand-Alone Torque Sensor Device

Fig 56

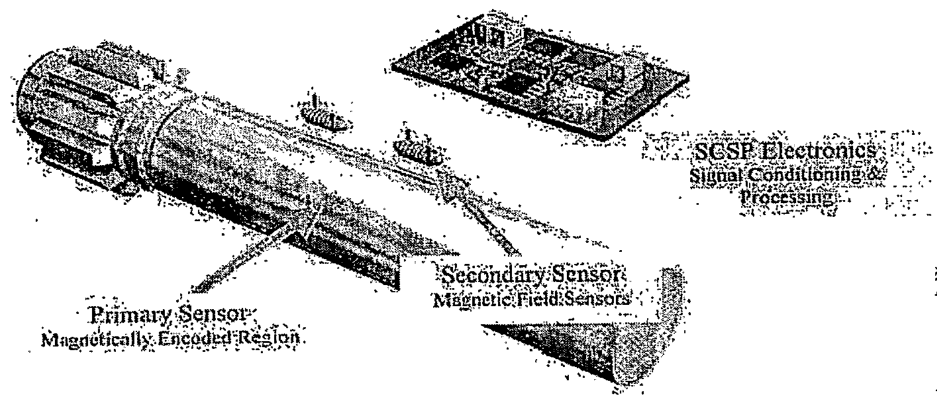

SCSP Electronics
Signal Conditioning & Processing
Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig 57

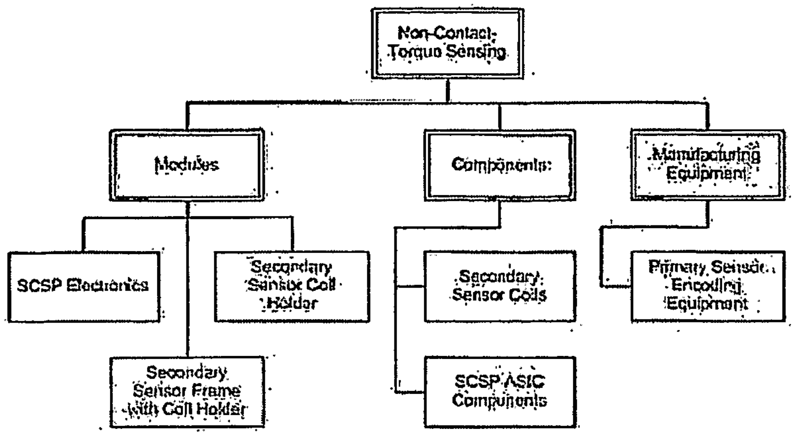


Fig. 58

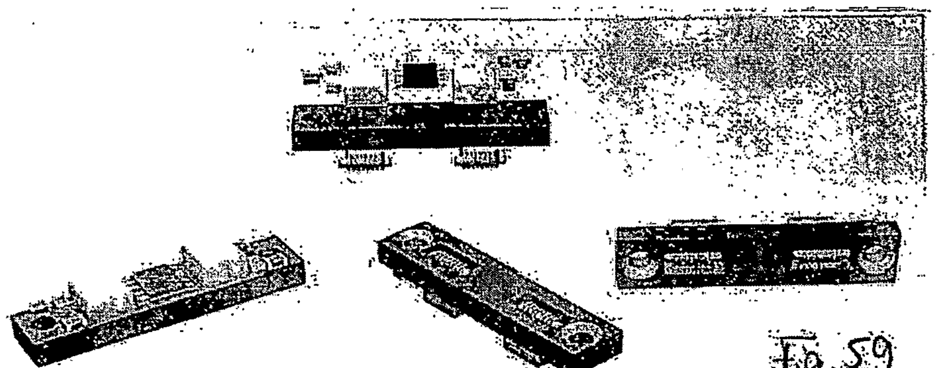


Fig. 59

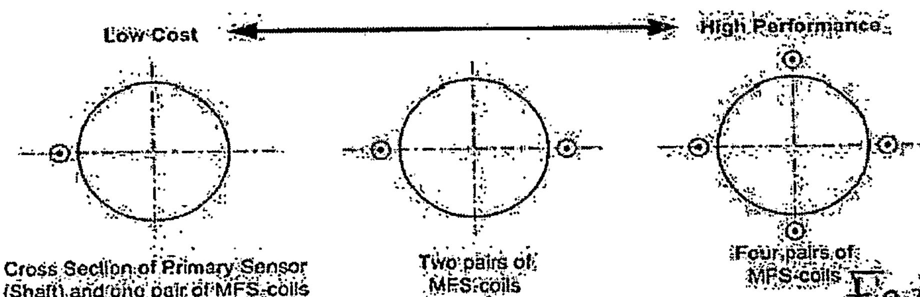


Fig. 60

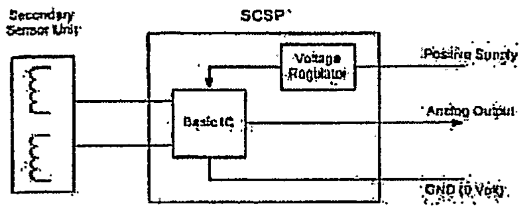

Secondary Sensor Unit
SCSP
Voltage Regulator
Basic IC
Positive Supply
Analog Output
GND (0 Volt)

Fig 61

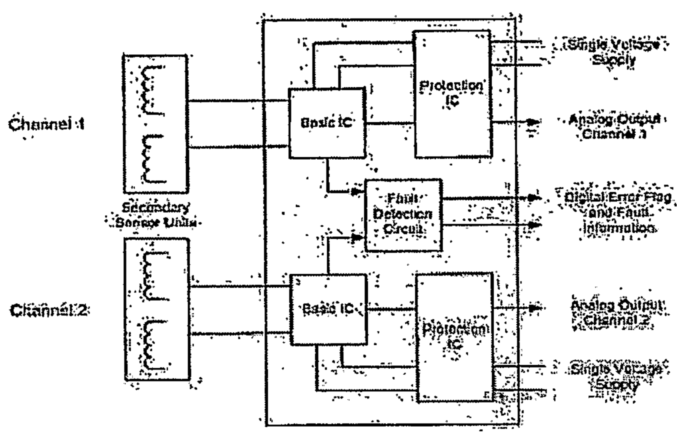

Channel 1
Basic IC
Protection IC
Single Voltage Supply
Analog Output Channel 1
Fault Detection Circuit
Digital Error Flag and Fault Information
Secondary Sensor Units
Channel 2
Basic IC
Protection IC
Analog Output Channel 2
Single Voltage Supply

Fig 62

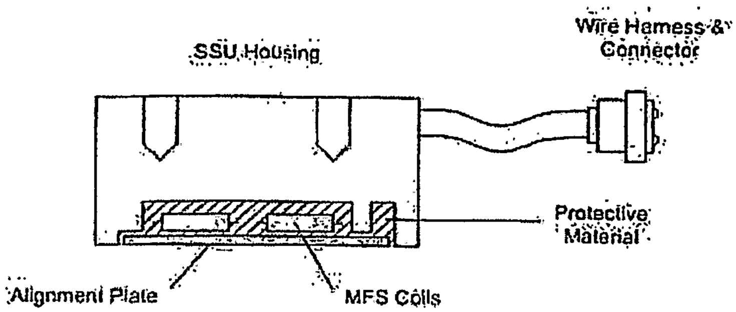

Wire Harness &
Connector
SSU Housing
Protective
Material
Alignment Plate
MFS Coils

Fig. 63

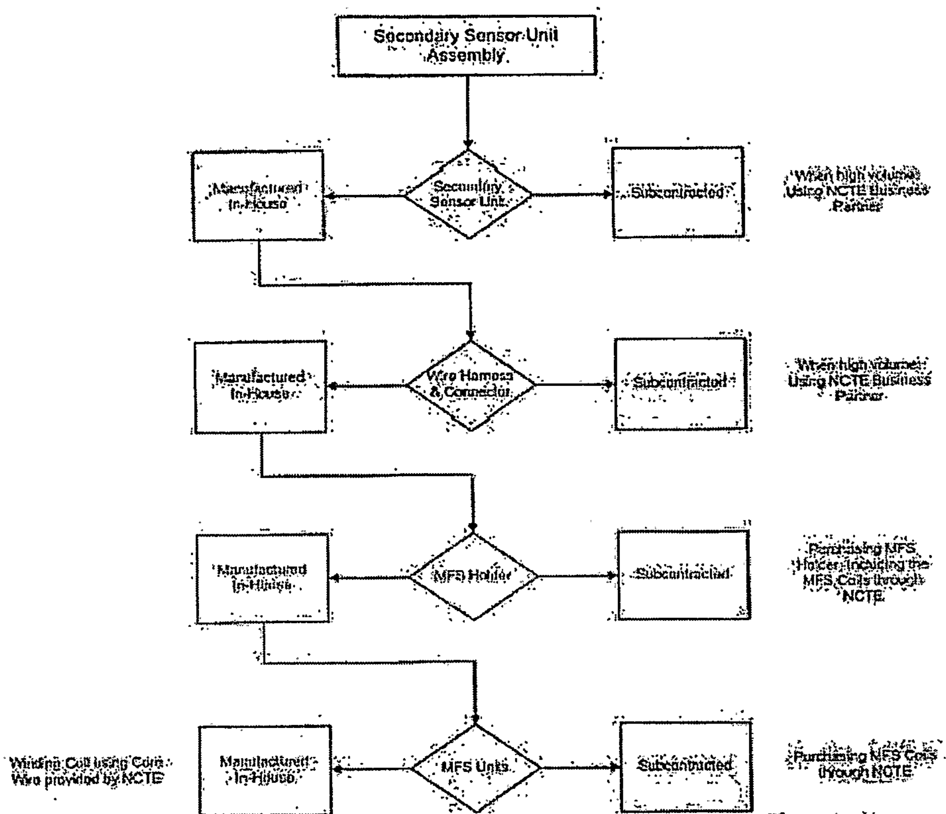

Secondary Sensor Unit
Assembly
Manufactured
In-House
Secondary
Sensor Unit
Subcontracted
When high volume:
Using NCTE Business
Partner
Manufactured
In-House
Wire Harness
& Connector
Subcontracted
When high volume:
Using NCTE Business
Partner
Manufactured
In-House
MFS Holder
Subcontracted
Purchasing MFS
Holder including the
MFS Coils through
NCTE
Winding Coil using Core
Wire provided by NCTE
Manufactured
In-House
MFS Units
Subcontracted
Purchasing MFS Coils
through NCTE

Fig. 64

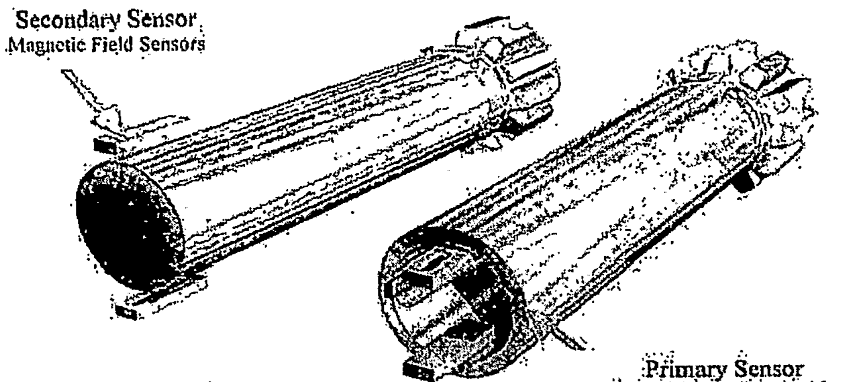

Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 65

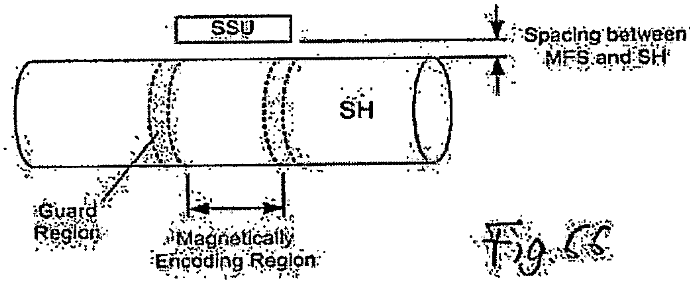

SSU
Spacing between
MFS and SH
SH
Guard
Region
Magnetically
Encoding Region

Fig. 66

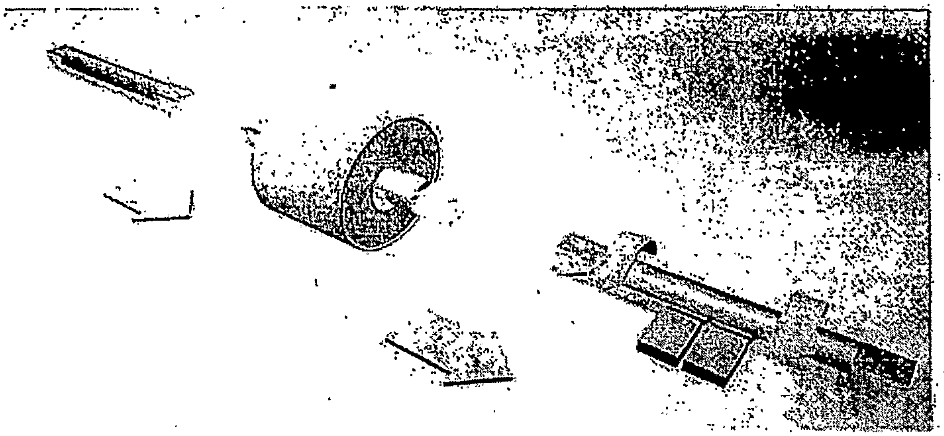


Fig. 67